TIME SECTION AND HODOGRAPH ANALYSIS OF CHURCHILL ROCKET AND RADIOSONDE WINDS AND TEMPERATURES

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[Manuscript received February 3, 1961

ABSTRACT

Winds and temperatures to above 80 km. measured during the International Geophysical Year by grenade, sphere accelerometer, and Pitot-static tube experiments at Churchill, Manitoba are combined with radiosonde data in time sections. The resulting analyses are discussed in reference to 10-mb. constant pressure charts showing the horizontal circulation near the 30-km. level. Periods in July, August, and December 1957 and January–February 1958 are covered.

The nature of the circulation in successive layers of the stratosphere and mesosphere is suggested by this investigation. In summer, irregular wind flow that is predominantly from the east appears in the middle and upper stratosphere. Strong easterlies in the lower and middle mesosphere are bounded in the upper mesosphere above 75 km. by a sharp vertical wind shear layer with highly variable west winds above, suggesting the existence of rapidly moving, intense cellular circulations near the mesopause. In winter when the boundary of the polar night is close to Churchill, such circulations seem to extend into lower layers until in January they occupy the entire mesosphere.

Strong west winds develop in the mid-stratosphere of wintertime, and a temperature minimum appears near the 30-km. level. During January 1958 the strong westerlies and the temperature minimum as well were disrupted by sudden warming of the entire stratosphere. The vertical structure of this warming effect, as it moved westward across the Atlantic and first appeared at the 40-km. level over Churchill, is shown by means of a cross section.

1. INTRODUCTION

Until recent years there has been a tendency to consider conditions from 20 to 90 km. above the earth either as quiescent or else dominated by zonal motions that change little from day to day but substantially from season to season. There has been great uncertainty about the magnitude of interdiurnal variations at these high levels. Data of the sort presented here help to shed light on this problem.

A remarkable series of temperature and wind observations was made at Churchill, Manitoba during the International Geophysical Year by means of grenades, sphere accelerometers, and Pitot-static tubes carried aloft in rocket vehicles. The grenade experiments are described, data presented, and copious references given by Stroud, Nordberg, and Walsh [15] and Stroud, Nordberg, Bandeen, Bartman, and Titus [13, 14], while accelerometer and static tube experiments are similarly described by Jones, Peterson, Schaefer, and Schulte [5, 6] and Ainsworth, Fox, and LaGow [1], respectively.

In this paper, the results of these experiments are presented in a somewhat different manner to bring out further details of the temperature distribution and circulation of the upper stratosphere and mesosphere. In each of the four cases discussed, radiosonde data are used to determine the analysis up to the 30-km. level during a two- or three-week period centered on the days of the rocket soundings. For higher altitudes, data from rocket experiments are available for two or more observations during each of the four periods. Many facets of the data and their meteorological implications already have been discussed in papers by those responsible for these experiments. Unavoidably, some points are repeated here in developing additional conclusions.

The reliability of conclusions drawn in the following discussion is determined by the accuracy of the data. Stroud et al. [14] state that the errors of the grenade experiment data below 75 km. are generally less than ± 3 C. for temperature, and ± 5 m.sec.$^{-1}$ and ± 15 degrees for wind speed and direction, respectively. Above 75 km. the size of the errors may increase rapidly by a factor of as much as ten at the very highest points. Jones et al. [5, 6] estimate the probable temperature error of the accelerometer experiment to be about 2 percent (4°–6° C.) below 75 km. and 5 percent (10°–15° C.) above 75 km. Furthermore, the dependence of the acceleration upon air density and drag coefficient limits the useful range of the experiment to the layer from 25 km. to 80 km. Temperatures from the static tube experiment are derived from density data having an estimated measurement error of less than 2 percent at 80 km. (Ainsworth et al. [1]).

The wind and temperature values given for the rocketsonde observations are averages for the layer between points at which two grenades exploded; thus, maximum

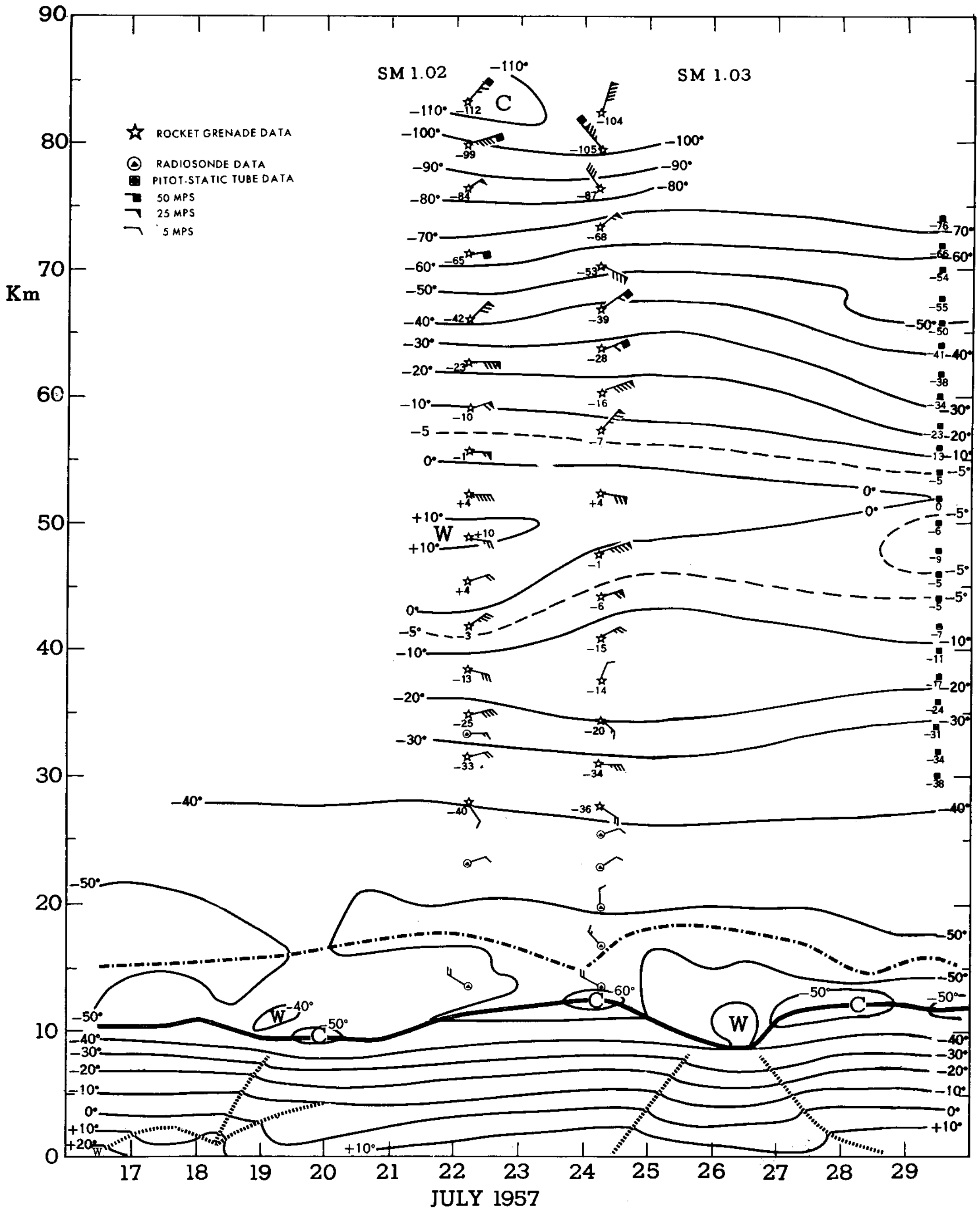

FIGURE 1.—Time section for Churchill, Manitoba, July 17–29, 1957, including data from rocket grenade experiments at 0416 GMT July 22 and 0530 GMT July 24, and a Pitot-static tube experiment at 2200 GMT July 29. Temperature analysis in °C. is based on radiosonde data below 30 km. and on grenade data at higher levels. Grenade temperatures and winds and selected winds from special radiosonde observations are included. Fronts given by dotted lines, tropopause by heavy line, thermal boundary by dash-dot line. C and W indicate cold and warm areas of diagram, respectively. Barbs representing wind speed are placed at the tail end of the wind shafts which point in direction toward which wind is blowing, with north at top of diagram and east at the right.

and minimum values tend to be smoothed out to some extent. Furthermore, random errors will have opposite signs in adjacent layers when the source of error is difficulty in accurate timing of sound arrivals from the grenade at the boundary between the layers. In excessively thin layers, less than 3 km., errors may be greatly magnified. Where highly incompatible values suggested such errors, the effect was minimized by combining adjacent layers.

2. THE CASES OF JULY AND AUGUST 1957

In their broad features, the time sections for July (fig. 1) and August (fig. 2) 1957 are remarkably similar. In the

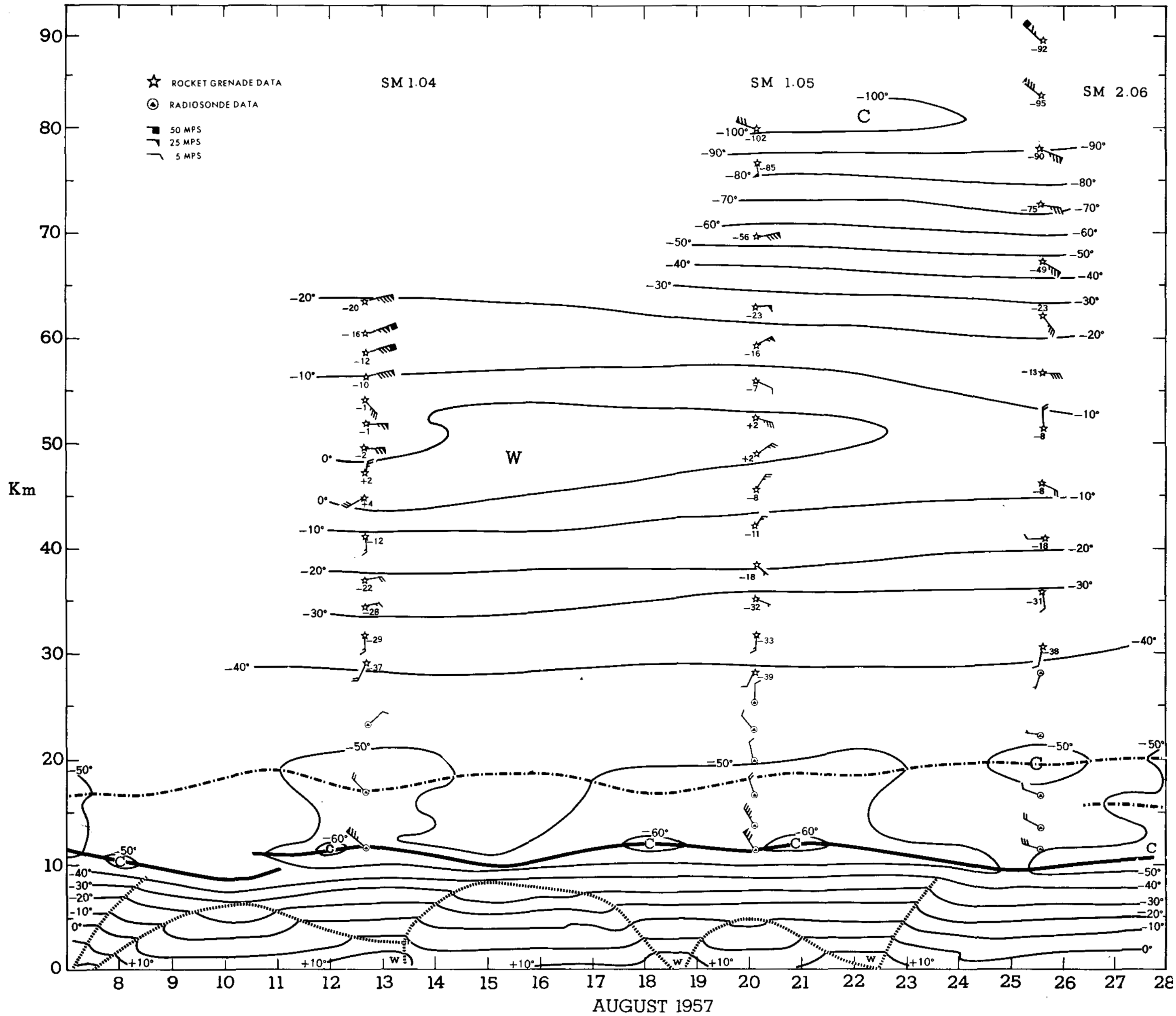

Figure 2.—Time section for Churchill, August 8–28, 1957. Rocket grenade experiments are for 1600 GMT August 12, 0230 GMT August 20, and 1408 GMT August 25. Explanation as in figure 1.

lower stratosphere, in each case, there was marked counteraction to tropospheric activity; e.g., warming occurred in this layer simultaneously with the tropospheric cooling following cold front passages. Vertical wind shear, operating in the troposphere to produce a wind maximum at the tropopause, was reversed within this layer so that light winds were found at the top of the layer. There, near 18 km., we find a poorly defined surface of minimum temperature having elevation changes out of phase and temperature changes in phase with those of the tropopause. This boundary seemed to mark the upper limit of tropospheric influence upon stratospheric conditions, for in the 20- to 30-km. layer the winds remained light and temperature constant from day to day. During the July period and continuing into the August period, the temperature varied by only a few degrees, suggesting that there was little vertical motion and almost perfect radiative equilibrium in the layer.

From 18 km. up to the stratopause, the thermal maximum at the top of the stratosphere near 50 km., the temperature increased from about −50° C. to about 0° C. The double temperature maximum at the stratopause on July 29 and again on August 12, already noted by Ainsworth et al. [1], is an interesting phenomenon that might

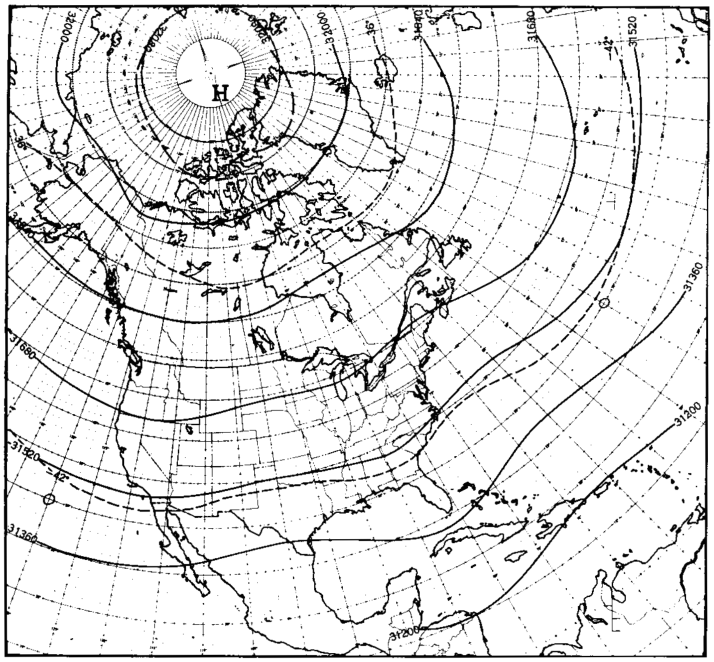

Figure 3.—10-mb. chart for 1200 gmt, July 25, 1957 (from [18]). Contours at 160-m. intervals; intermediate contours given by long-dashed lines; isotherms given by dashed lines at 6° C. intervals. H is for high pressure center, L for low pressure center.

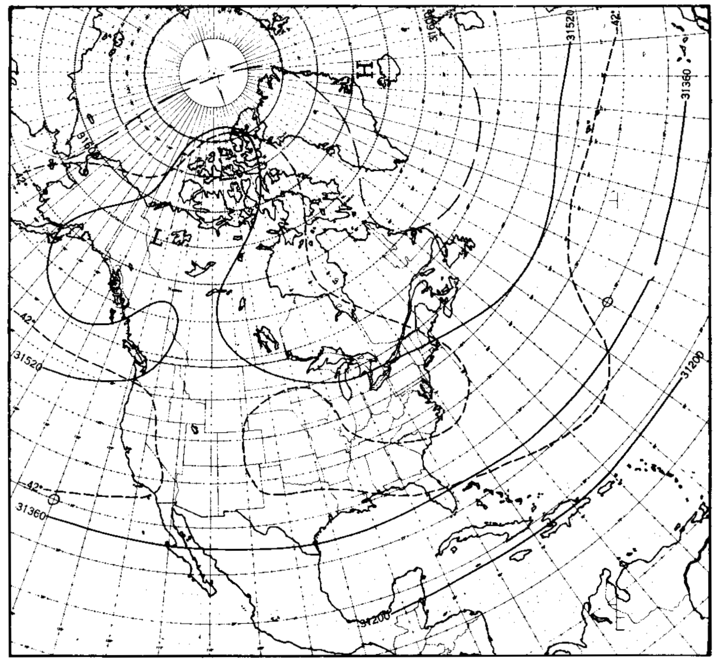

Figure 5.—10-mb. chart for 1200 gmt, August 25, 1957 (from [18]). Explantation as in figure 3. Colder air is in the Tropics and near low center in Canada.

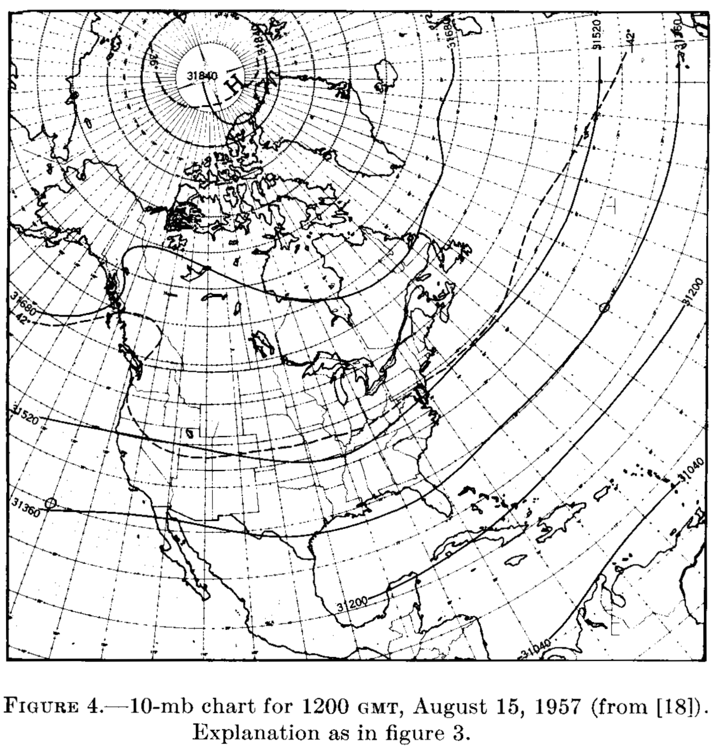

Figure 4.—10-mb chart for 1200 gmt, August 15, 1957 (from [18]). Explanation as in figure 3.

be due either to differential heating of layers or to advective processes. In the mesosphere above 50 km., the temperature decreased slightly up to 60 km. but then decreased at an average rate of 4° C. km.$^{-1}$ up to about 80 km. Although on July 24 and again on August 25 a surface of minimum temperature defining the mesopause or top boundary of the mesosphere appeared near 80 km., the rate of temperature rise above that level was very slight.

During July, winds at 10 mb. (30 km.) over North America were everywhere from the east as illustrated by contours of figure 3. On July 22 and 24 at Churchill (fig. 1), the east wind tended to increase with height above 30 km. to speeds exceeding 50 m. sec.$^{-1}$ in the middle and upper mesosphere where the wind backed to northeast or northerly. If the temperature variation between the two observations and the isotherm gradients indicated by the wind shears are taken at face value and interpreted with the aid of the thermal wind equation, the conclusions made in the following paragraphs are valid.

The air in the 40- to 50-km. layer cooled by about 7° C. in the 2-day period. The change of vertical wind shear from easterlies diminishing with height to easterlies increasing with height requires that greater cooling took place to the south of Churchill than to the north.

In the layer from about 45 to 64 km., the observed vertical wind shear of about 2 m. sec.$^{-1}$ km.$^{-1}$ would have required a north-to-south temperature gradient of 7° C. in 10° of latitude, although this rate of horizontal temperature variation would have had to extend beyond the vicinity of Churchill only if vertical wind shear did also. However, since the actual wind was nearly parallel to the thermal wind, the advective wind was negligible and little horizontal temperature advection or vertical motion along isentropic surfaces is indicated.

At 83 km. on July 22, a remarkably low layer-mean temperature of −112° C. was reported; the decrease of easterly wind speed reported between 80 and 83 km. would have permitted even lower temperatures to the north of Churchill.

By the end of August (fig. 2) temperatures in the troposphere and middle stratosphere were about 5° C. cooler than in July. Cooling was more marked at the stratopause where the temperature was more than 10° C. lower on August 25 than on July 22. The north-to-south temperature gradient that was present in July in the upper stratosphere near Churchill seems to have been destroyed by August 25 when the winds in that layer showed no definite vertical shear. This apparently signals the beginning of that part of the year when temperatures near the level of the stratopause decrease toward the north. Indeed, the 10-mb. charts for August 15 and 25 (figs. 4 and 5) show that such seasonal temperature and wind changes were taking place in the middle stratosphere with gradual formation of a cold Low over northwestern Canada. The 10-mb. temperatures for the remainder of the year at Churchill continued to decrease, particularly rapidly in September and October. Westerly winds appeared at 10 mb. early in September and increased in strength throughout the autumn.

In the mesosphere up to 65 km. during August, a persisting north-to-south temperature gradient is indicated by the increase of the easterly wind component with height. Although the August 12 sounding was cut off near 65 km., it shows easterly winds as strong as those reported in July. However, in the 50–75-km. layer of the mesosphere, the two later August rocket soundings show progressively lighter easterly components and lower temperatures.

Near the mesopause there was a pronounced vertical wind shear with wind shifting from strong easterly to strong westerly, indicating a strong horizontal temperature gradient of about 2° C. per latitude degree toward the north in the 70–80-km. layer on August 20 and 4° C. per latitude degree in the 78–83-km. layer on August 25. The temperature of the mesopause was progressively warmer in each observation from July 22 to August 25. However, the horizontal temperature gradient required by the vertical wind shear across the mesopause on August 25 would have permitted the −112° C. temperature of the July case to be found only 5° latitude to the north of Churchill.

Murgatroyd [9] presented a vertical temperature distribution for summer at 60° N. that is confirmed in most respects by the Churchill summer soundings. Among the principal points of difference are his relatively high temperatures of +21° C. and −93° C. at the stratopause and mesopause respectively. His temperatures for the mesosphere between these levels do not differ greatly from those of the grenade experiments since he gives a greater temperature lapse rate immediately above the stratopause and a lesser lapse rate just below the mesopause than do the grenade experiments. The lapse rates of the grenade experiments thus favor a maximum of vertical mixing in the layers just below the mesopause. The winds observed differ in two respects from those given by Murgatroyd for summer conditions near 60° N. The Churchill data indicate higher wind speeds, exceeding 25 m. sec.$^{-1}$ in the 60- to 75-km. layer, and a shift to west winds near 80 km. elevation instead of near 90 km.

3. THE CASE OF DECEMBER 1957

The time section for December 6–20, 1957 (fig. 6) shows a troposphere 25° C. colder than it was in summer. Above the tropopause, with average height about 1 km. less than in August, the lower stratosphere had cooled only 10° C. The middle stratosphere underwent more remarkable changes, the wind having increased to westerly 25 to 50 m. sec.$^{-1}$ as a 30° C. decrease of temperature at 28 km. produced an inversion base at that altitude. A broad trough with coldest air at the pole dominated Canada at the 30-km. level (fig. 7).

Like the lower stratosphere the stratopause cooled only 10° C. The position of the stratopause at 51 km. is at variance with the position near 60 km. given by Murgatroyd [9] for winter at this latitude. In fact, these experiments show a remarkable temperature minimum near 60 km. The height of the stratopause in January (fig. 8) was indefinite but somewhat closer to 60 km. The extreme temperature changes above 60 km. during the December 12–14 period are in strong contrast to the regularity in temperature patterns of the summer mesosphere. Coupled with winds in the neighborhood of 100 m. sec.$^{-1}$, these temperature changes suggest the existence of violent storms in the winter mesosphere, albeit they are tempests in a near vacuum. Determination of the geographical extent and speed of motion of these storms requires a synoptic network of rocketsonde stations such as that now being activated over North America.

The wintertime temperatures of the upper mesosphere at Churchill were much warmer than those measured there in summer or at lower latitudes in winter. Although warming in the stratosphere and mesosphere is generally explainable by a reasonable amount of sinking and compression of air from higher layers, Kellogg [7] has described a process by which heat may be liberated at or above the mesopause through recombination of atomic oxygen brought down from ionospheric layers rich in this element.

4. THE CASE OF JANUARY–FEBRUARY 1958

Even before the rocketsonde data became generally available, the radical changes in stratospheric circulation and accompanying explosive warming of the stratosphere during the weeks following mid-January 1958 had been the subject of several papers (Boville [3]; Palmer [10];

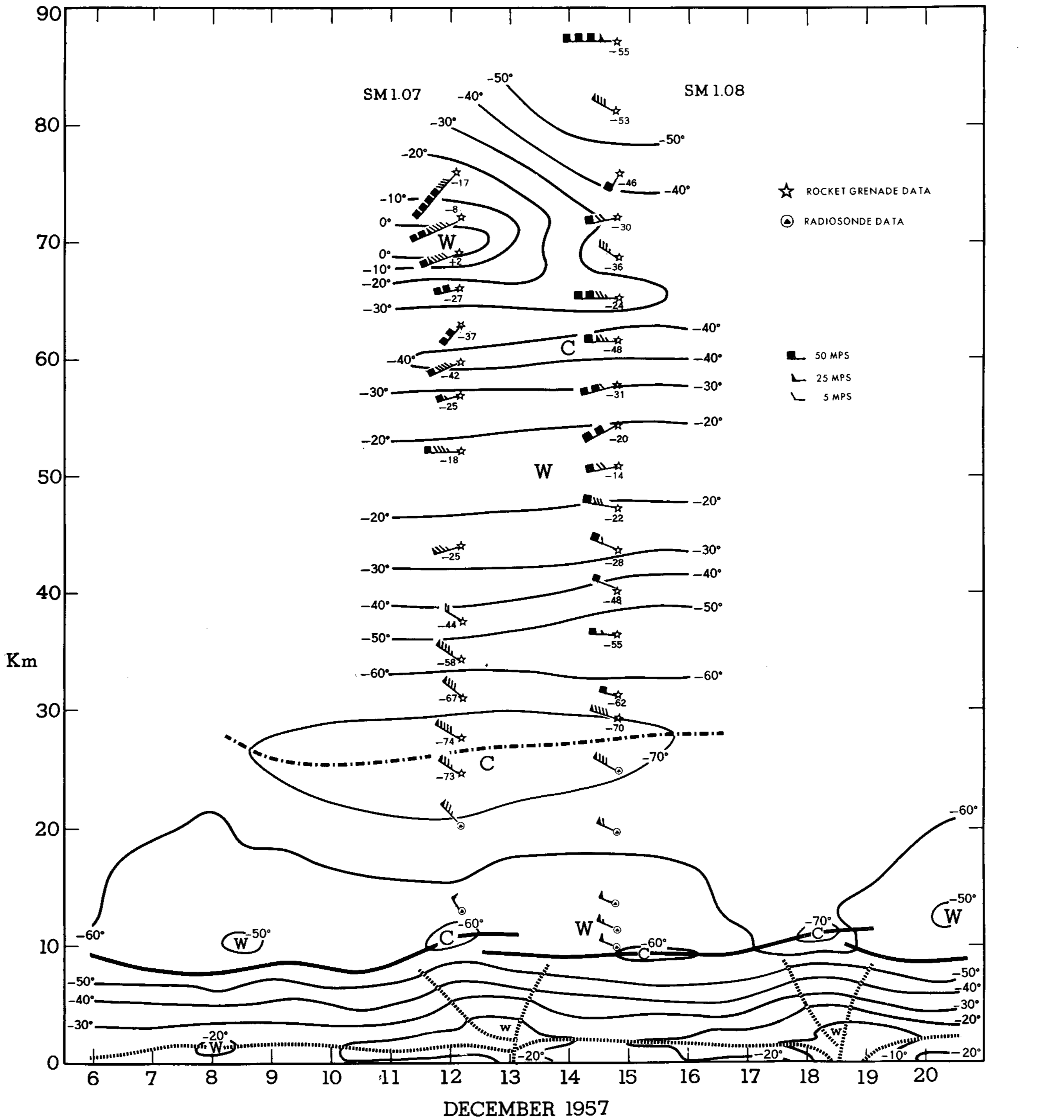

Figure 6.—Time section for Churchill, December 6–20, 1957. Rocket grenade experiments were at 0400 GMT December 12 and 2100 GMT December 14. Explanation as in figure 1.

Scherhag [11, 12]; Teweles and Finger [16]; Teweles, Rothenberg, and Finger [17]).

Because most frontal activity in the troposphere was displaced far to the south of Churchill during the period January 22 to February 6, only relatively minor changes in tropopause height and temperature are revealed in figure 8. In the lower stratosphere, unusual warming after January 26 culminated in a temperature of −41° C. at 100 mb. on February 3. In mid-stratosphere by January 25, the 30-km. temperature had dropped below −70° C., and by January 27 the altitude of the temperature minimum was raised to 33 km. This temperature minimum was depressed to 25 km. in the succeeding days as strong warming occurred in the upper stratosphere.

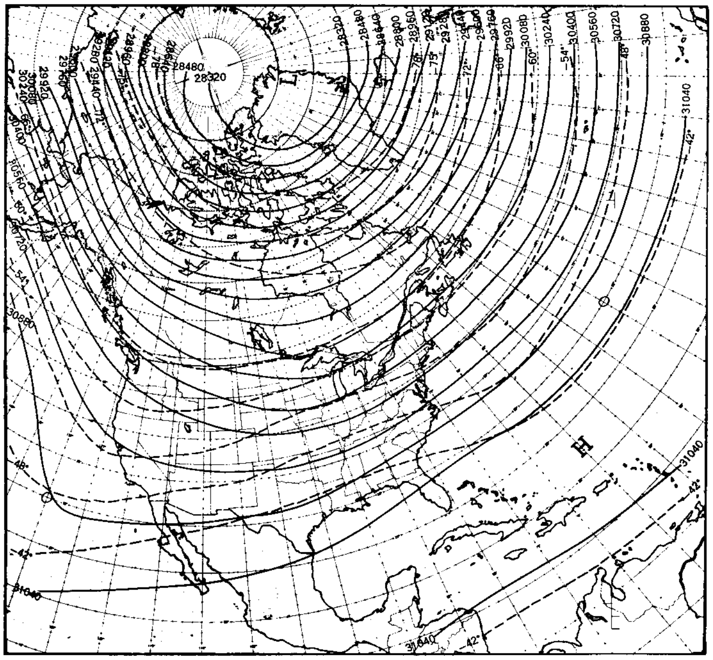

FIGURE 7.—10-mb chart for 1200 GMT, December 15, 1957 (from [18]). Explanation as in figure 3.

For the period January 25 to 29, an unprecedented concentration of rocket sounding data is available for reconstructing conditions at high levels. Accelerometer spheres launched by Nike-Cajun rockets on January 25 and 29 gave both up-leg and down-leg information. Down-leg information was given by a similar sphere, borne by one of two grenade-carrying Aerobee rockets launched on January 27. The temperatures derived from these accelerometer experiments become consistent with radiosonde data at and above the 25-km. level, and above the ceiling of the radiosonde data remain consistent internally and with grenade data up to 65 km.

Warming took place slowly at Churchill between 40 and 45 km. from January 25 to 27, then rapidly between 30 and 60 km. from January 27 to 29. The 4-day temperature increase of almost 70° C. in the 38- to 41-km. layer at Churchill is greater than any ever recorded at lower levels.

The circulation and thermal structure at levels above 30 km. on January 27 can be reconstructed by hodograph analysis (fig. 9) of grenade experiment winds for that day (shown on fig. 8). From the tropopause up to 65 km., there is remarkable agreement in the winds from these two experiments. A southwest wind of 30 m. sec.$^{-1}$ was observed just below the tropopause at 8 km. as a trough approached from the west. The wind decreased upward to a minimum near 14 km. and increased again to a maximum of about 75 m. sec.$^{-1}$ from the north-northeast at 33 km. The resulting shear vector in the 8- to 33-km. layer placed the warmest air toward the northwest. Thus there was a cold Low to the east and a warm High to the west of Churchill with maximum intensity at 33 km. There have been few cases in which the level of a polar night jet stream of such strength has been so clearly defined. Above the 33-km. level, the decrease in strength of the jet required a reversal of temperature gradient. Thus the Low became a warm Low and the High became a cold High, both systems decreasing in strength with elevation. These features characterize the 33-km. level as a null level, as described by Faust and Attmannspacher [4] (or see Lamb [8]).

Near the 45-km. level the wind shifted around through easterly to become strong southerly at 52 km. Apparently the vertical axis of low pressure sloped from east to west across the Churchill area at about the 45-km. level, with the low center itself south of Churchill at that level. The south wind increasing with height in the 45- to 52-km. layer required a warm High to the east and a cold Low to the west, both systems increasing in strength with elevation to at least 52 km. The advective wind in the 33- to 52-km. layer can account for a warming of about 30° C. in two days. Since a warming of 60° C. was actually observed at 40 km. during the two days ending on January 29, and since the final temperatures are undoubtedly anomalously high for that level, subsidence as well as advection must be called upon to explain such a great warming.

Above 52 km. the circulation apparently retained its general form and strength to at least 75 km. Although the reported winds were very erratic, mean winds for overlapping 10-km. layers up to 75 km. were quite consistently from the south.

As in the December case, the alternation of warm and cold air layers was in sharp contrast to the steep lapse rate of the summer mesosphere, and the temperature in the upper portion of the mesosphere was much warmer than in summer.

In the 0604 GMT sounding, a remarkably strong west wind was reported along with high temperature at 79 km. By 1845 GMT, west winds were reported at all levels above 77 km. Expansion of the warm layer near 80 km. during the next two days is indicated by the falling-sphere data. Here we see the approach to Churchill of a system similar to that which moved away from Churchill between December 12 and 14. The reality of the large variations that are reported in wind speed and direction from one level to the next or between observations only a few hours apart must be more firmly established before great confidence can be placed in the features of the circulation inferred from the observations. Even so, it is now certain that the wintertime circulation of the mesosphere, in the subarctic, is very active and thus of very special interest to the meteorologist.

5. EVENTS IN SURROUNDING AREAS AT TIME OF WARMING AT CHURCHILL

The 1200 GMT 10-mb. charts for January 25 (fig. 10), U.S.

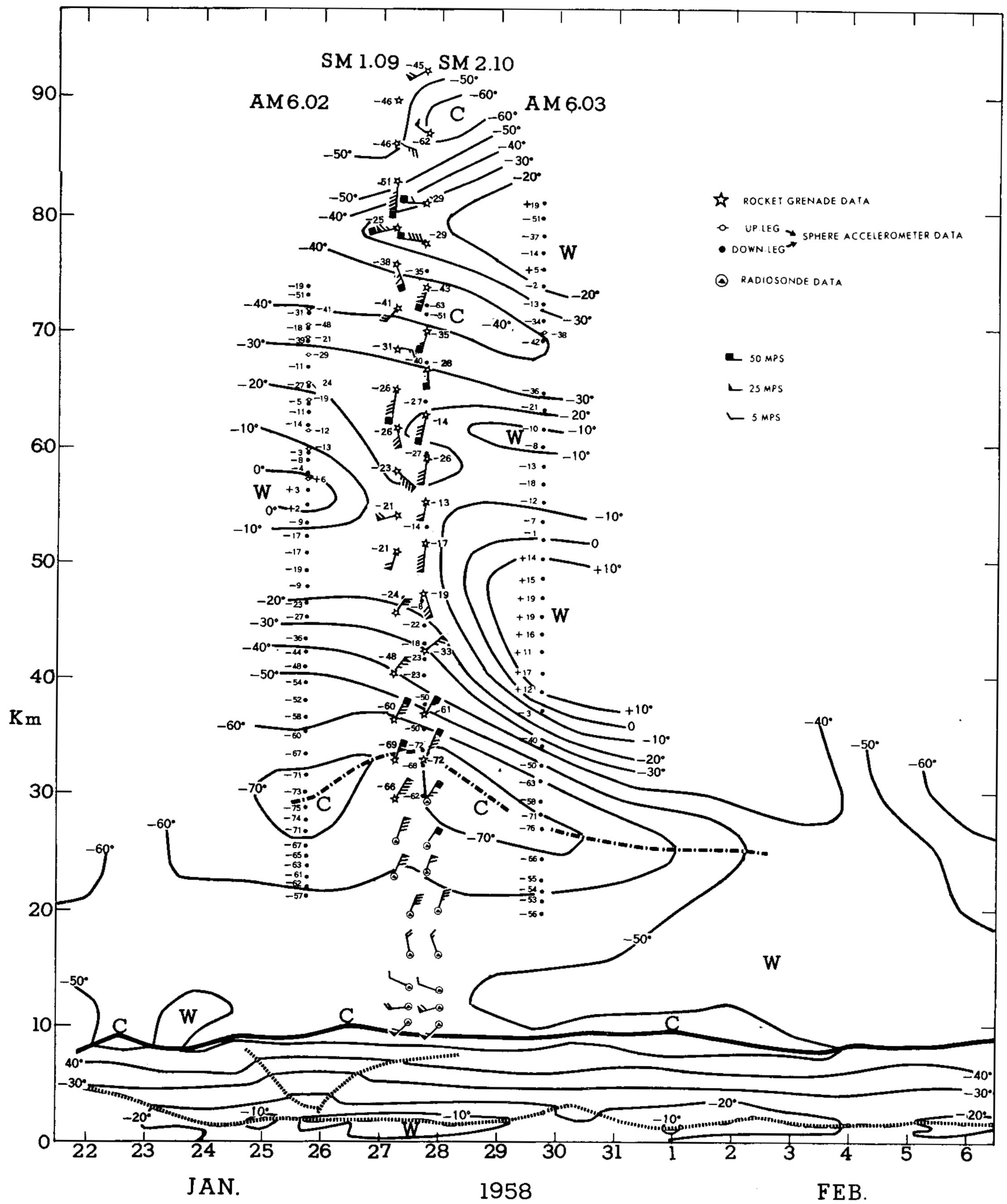

Figure 8.—Time-section for Churchill, January 22–February 6, 1958. Rocket grenade experiments were at 0604 GMT and 1845 GMT January 27. Sphere accelerometer experiments were at 1912 GMT January 25, 1845 GMT January 27, and 1906 GMT January 29. Explanation as in figure 1.

Weather Bureau [18], and for January 29 (fig. 11), Behr et al. [2], help to place the Churchill rocket sounding data near the 30-km. level in perspective with events that were taking place in surrounding portions of the hemisphere. These charts confirm the existence of the relatively cold Low revealed by the wind and its vertical variation near this level on January 27. In the 4-day interval, this Low rapidly approached Churchill from a position over southern Greenland. Meanwhile, the warm High in the Gulf of Alaska moved poleward across Alaska into the Arctic Ocean.

During early January, a section of the polar night jet stream, which was nearly circumpolar in December (fig. 7), slowly arched poleward across Alaska. By January 25, the axis of this current stretched across the North Pole southward toward Churchill, and the Arctic was being ventilated with warm air from sunlit latitudes. The exceedingly cold air that formerly occupied the Arctic

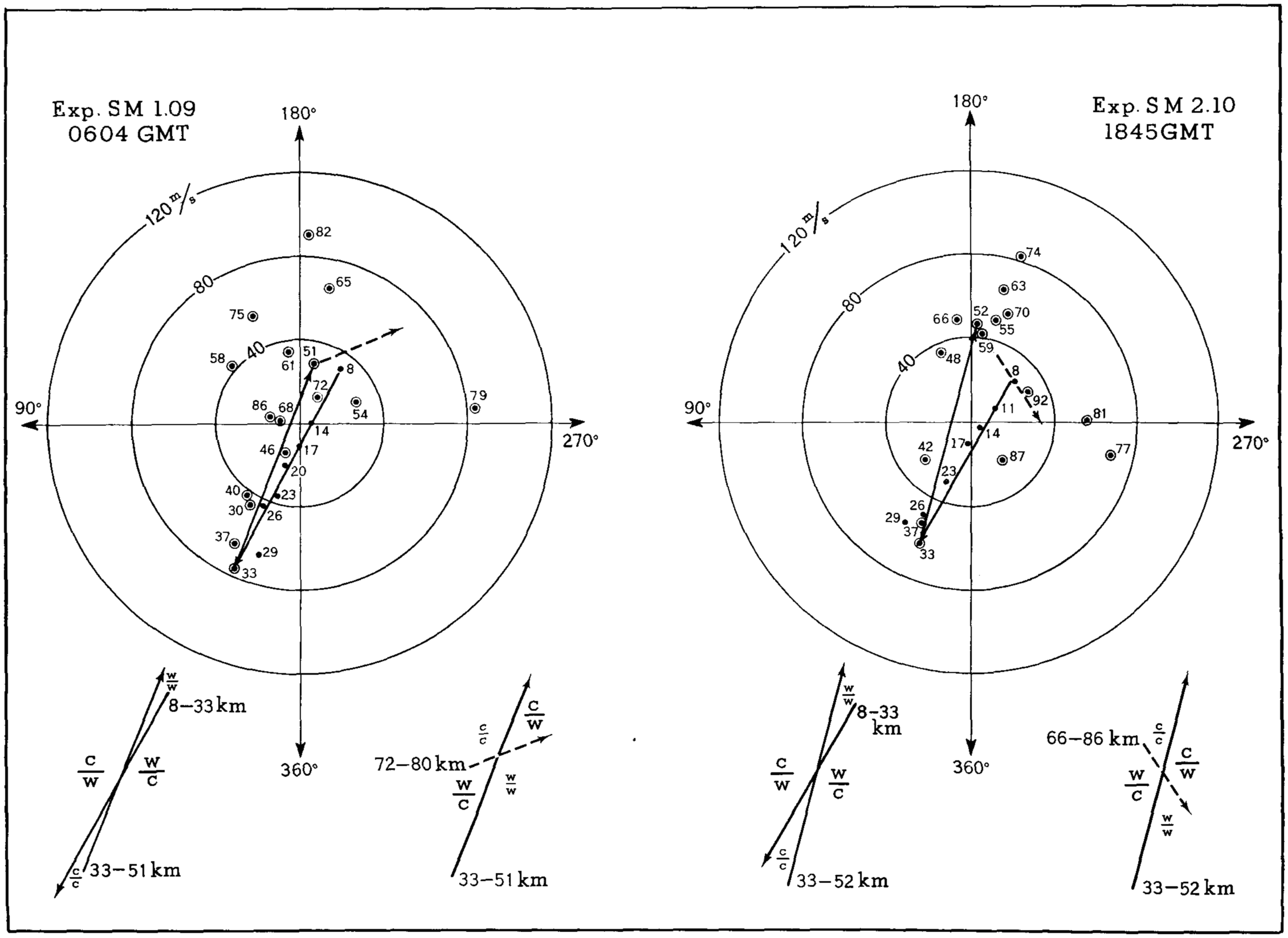

FIGURE 9.—Hodographs of the wind observations plotted in figure 8. Radiosonde winds given by dots to represent head of arrow with tail at origin; arrow points in direction wind is blowing. Circled dots represent grenade experiment winds, numbers at dots give height of mid-point of layer to the nearest km. Arrows in diagram give vertical wind shear in layers having relatively uniform shear. Two or three points were averaged where indications were indefinite. Shear arrows for layers are superimposed below hodograph. Relatively warm direction in the shear layer is indicated by W, cold direction by C; thus, W/C indicates the direction of greatest static stability with relatively warm layer lying above relatively cold layer. Near 60 km. there is a neutral layer without significant shear lying between layers with shear. Shear of the highest layers, given by dashed arrow, is somewhat indeterminate.

split into two cells, one associated with low pressure over Siberia (see Behr et al. [2]), the other centered in the western portion of the low pressure area approaching Churchill from the east.

Hodograph analysis for January 27 (fig. 9) when applied to the 10-mb. circulation pattern leads to several interesting conclusions. The polar night jet stream at Churchill had its maximum strength at 33 km. above which it lost strength. Further interpretation is suggested by the pattern of contours and isotherms found at 10 mb. on January 25. The axis of the 10-mb. Low center, located just southeast of Hudson Bay on January 25, from hydrostatic considerations must have sloped with elevation in the direction of coldest air. If the axis of coldest air also sloped in the same direction and the contour-isotherm relationship did not change with height, the vertical wind structure at Churchill can be explained quite convincingly. At 33 km., where the wind shear direction reversed, the cold air was centered directly over Churchill, but the low pressure center was still to the east. Above 33 km., the cold air was centered west of Churchill to at least 51 km., but northerly winds show that the low center remained to the east and southeast up to 45 km. At this level the Low in its westward movement passed south of Churchill between observations. The uniformly strong wind shear between 37 and 52 km. showed the presence of a tight temperature gradient with warmest air toward the east, like that in the southeast quadrant of the Low at 10 mb. (figs. 10 and 11).

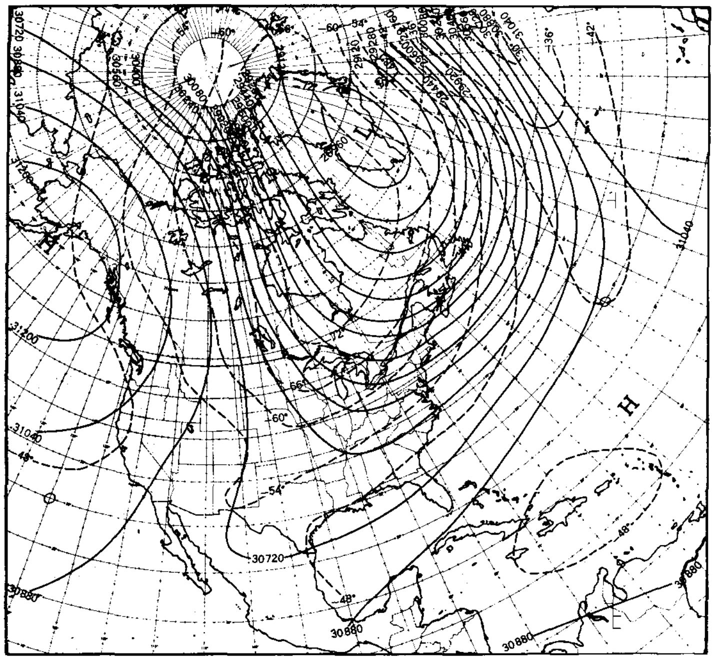

FIGURE 10.—10-mb. chart for 1200 GMT, January 25, 1958 (from [18]). Explanation as in figure 3.

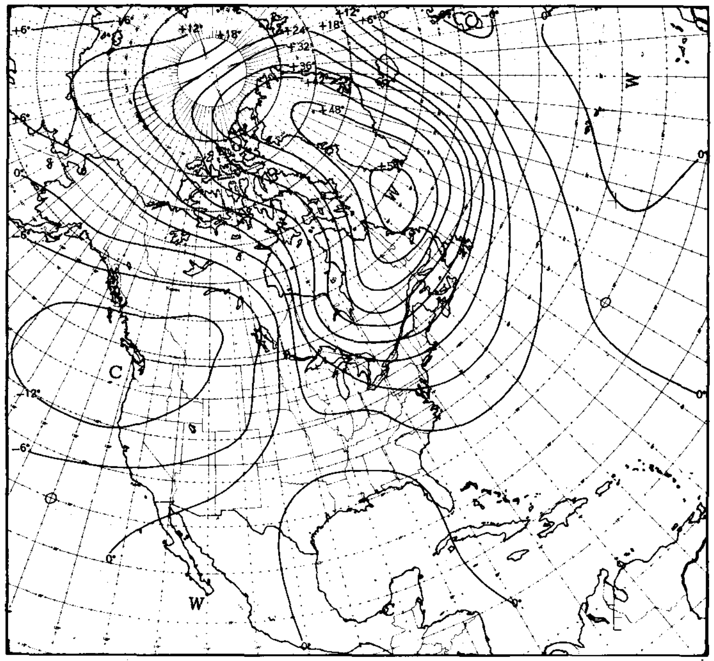

FIGURE 12.—Temperature change in °C. at 10mb. in the 4-day period January 25–29, 1958, obtained by graphical subtraction of isotherm patterns in figures 10 and 11. W indicates area of warming, C area of cooling.

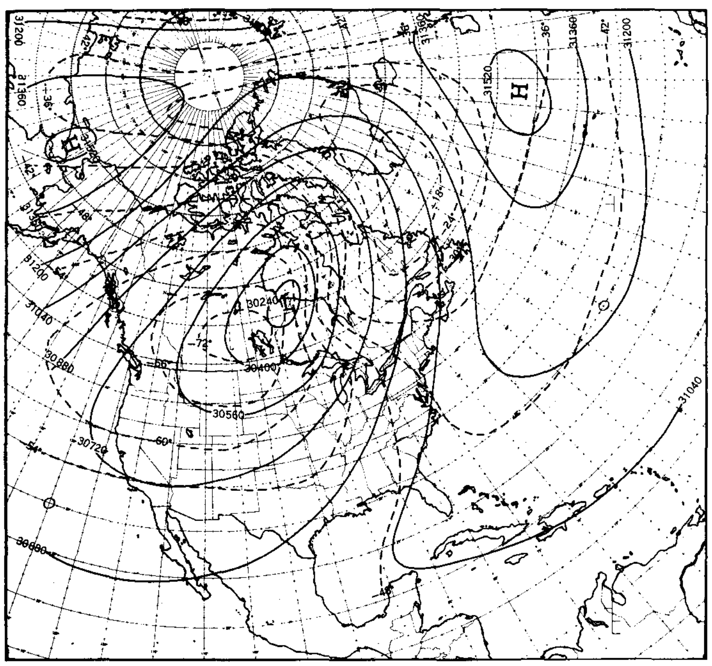

FIGURE 11.—10-mb. chart for 1200 GMT, January 29, 1958 (data from [2]). Explanation as in figure 3.

The 4-day temperature change at 10 mb., computed from the isotherm patterns of January 25 and 29 (fig. 12), shows a remarkable rise of more than 54° C. in the region between Greenland and Labrador. The even larger temperature change at the 40-km. level above Churchill during the same period was most certainly connected with the warming farther east at 10 mb. This gives convincing proof of the tremendous lateral shift with altitude of stratospheric patterns. In this case, the leading edge of the warming sloped upward 10 km. in a horizontal distance of 2,000 km., the same 1:200 slope typical of warm front surfaces in the lower troposphere.

If the wind reversal near 45 km. is taken as evidence that the low-center position was very close to Churchill at that level, and if the low-center position at 30 km. is taken from the January 27 10-mb. charts of Behr et al. [2], then the axis of the low center tilted westward 1,500 km. in a vertical layer 15 km. deep, a slope of 1:100. The 1:200 slope of the warm air indicates that it was overspreading the top of the low center to diminish the intensity of the center first near 40 km. and gradually at lower levels. The net effect is demonstrated by the great loss of kinetic energy at 30 km. over North America during the following week and over the remainder of the hemisphere by mid-February (see 10-mb. charts in Behr et al. [2] or U.S. Weather Bureau [18]). Simultaneously, the general level of the 10-mb. surface in the Arctic was substantially raised.

A cross-section from Naknek, Alaska through Churchill to Berlin, Germany on January 29 (fig. 13) illustrates the great horizontal and vertical extent of the warming at the time of the 40-km. warming at Churchill. Cooling with the advance of the cold sliver near 30 km. in the lower forward portion of the system is almost as impressive as the warming in the upper rear portion. While the cooling did not produce temperatures that were anomalous for the entire hemisphere as did the concomitant warming, it did

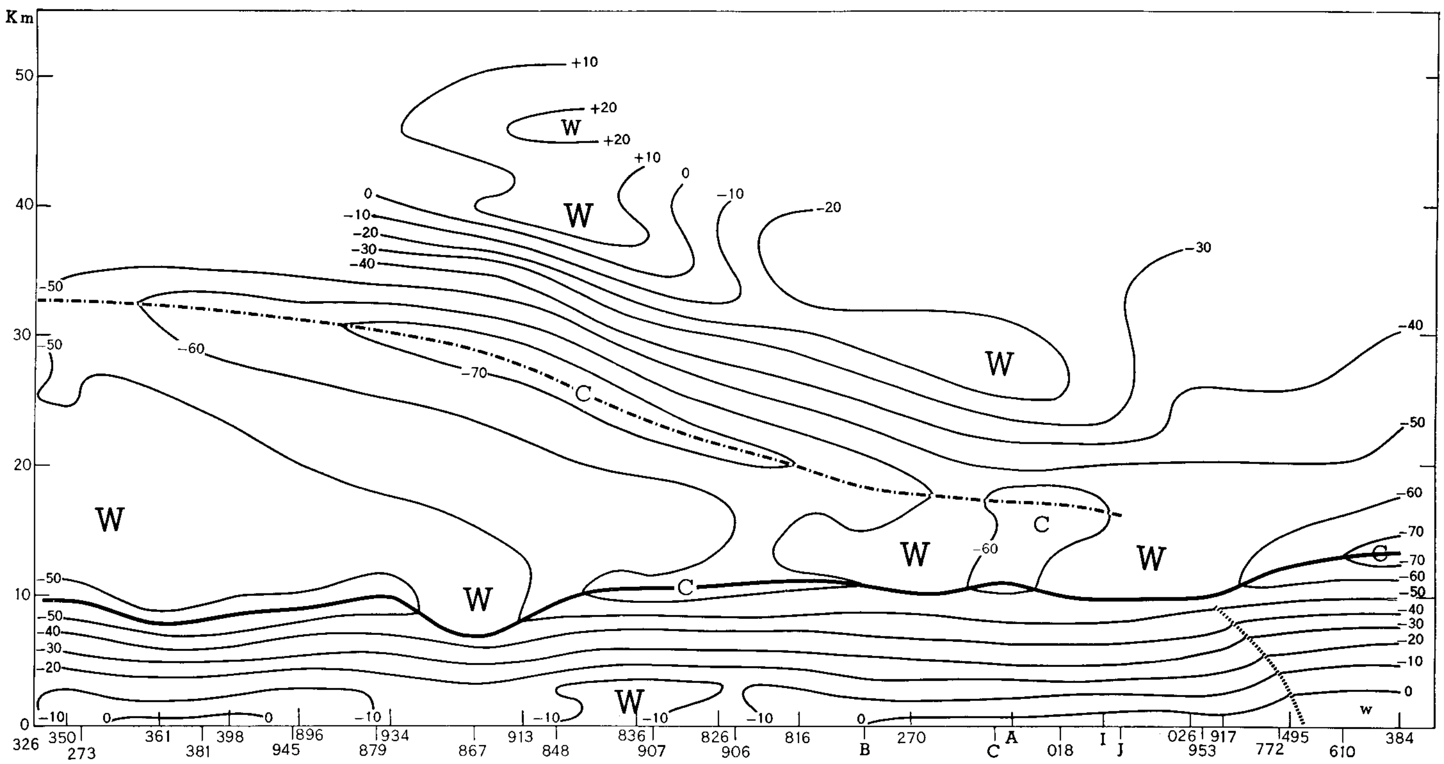

Figure 13.—Cross section, January 29, 1958, near 55° N. from Naknek, Alaska (station 326) through Churchill (station 913) to Berlin Germany (station 384). Explanation generally as in figure 1. Temperature analysis at high levels in vicinity of Churchill is based entirely on sphere accelerometer experiment AM 6.03 for 1906 GMT. Identification numbers of radiosonde stations from which data were used are shown along bottom of chart at projected location of station.

bring anomalously low temperatures into the middle latitudes. All indications are that the stratospheric features in the cross-section were slowly moving toward the west. Thus, the warmest air at 25 km. crossed over Berlin on January 25, passed to the south of Greenland on January 29, as shown in figure 12, and then diffused across North America in the first three days of February.

Figure 8 shows the upwelling of the coldest air to above 30 km. that immediately preceded the intensive warming near the 40-km. level. The core of the polar night jet stream seems to have been wedged between these layers of climactic cooling below and incipient warming above.

The interaction of vertical motions and jet stream accelerations around the vertically tilting core of low pressure must account for the observed temperature and pressure changes. Two-dimensional sections do not reveal the exact linkage by which these motions are maintained for long periods in a tremendous volume of atmosphere. However, increasingly detailed descriptions of these phenomena may eventually lead to a successful mathematical formulation of the problem.

6. CONCLUSION

The temperature and wind observations utilized in this paper were among the first to become available to great heights at such high latitudes. The large amount of information deduced from this limited number of soundings is a strong recommendation for gathering much more temperature and wind information to the highest possible levels.

That there are several layers of the atmosphere having their own characteristic types of horizontal circulation is brought out by the charts displayed in this paper. Undoubtedly, the dominating cause is the division of the atmosphere into layers of radically different static stability by the variable effectiveness of its constituents in absorbing radiation at different altitudes, latitudes, and seasons. However, the circulation at any level is tied hydrostatically to the circulation at adjacent levels by the temperature distribution in the intervening layers. Feedback of energy from one level to another may be great or small depending upon the static stability, baroclinicity, and relative pressure and kinetic energy difference between the levels; thus accurate measurement of these parameters is important for future research studies.

High static stability is the only significant unique quality of the stratosphere available to explain the relatively slow development and large size of stratospheric systems compared to those of the troposphere. In developing, these systems carry the seeds of their own destruction, for baroclinicity is dispersed and destroyed as the cold pool is transported from the darkness of the

Arctic into the sunlit latitudes while warm air floods the polar regions. Thereafter the long slow process of formation of a new cold pool in the Arctic must begin again and continue until interrupted by the development of another perturbation or by radiational heating from the returning sun. The upper limit of the layer in which this process takes place has been the subject of much speculation. Strategically planned rocket firings near the poles in winter will certainly help to answer this problem.

Much about the nature of the circulation in the upper stratosphere and lower mesosphere has been revealed by these and other rocket soundings. However, if anything, the nature of the circulation in the upper mesosphere has become more of a mystery. Even though diurnal and semi-diurnal effects and errors in measurement are large near the mesopause, the data presented here indicate that the circulation of nearby layers is really quite active, particularly so in winter through a deep layer at the boundary of the polar darkness.

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